Analysis of 802.11 OFDM in High Multipath Environments

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***Abstract*—The performance loss of 802.11 OFDM systems due to propagation delay spread has been analyzed as a function of OFDM parameters for a wide range of reverberation times. This analysis results into solutions for the OFDM design to suppress the performance degradation.**

***Index Terms*—delay spread; diffuse multipath; reverberation time; OFDM; room electromagnetics**

I. Introduction

The performance of OFDM (orthogonal frequency-division multiplexing) systems can be degraded by the signal distortion over the FFT (fast Fourier transform) window caused by the propagation delay spread. In [1], we proposed to describe this effect in narrowband OFDM systems (such as IEEE 802.11a/g/n/ac) by an additive white Gaussian noise (AWGN) noise, characterized by a noise factor F_{delay}. This effect originates from replicas of the transmitted OFDM pulse with a delay larger than the cyclic prefix length CP. The intensity of these propagation paths can be high, especially in indoor environments, resulting into intersymbol and intercarrier (ISI/ICI) interference. For delays higher than CP, the channel typically consists of diffuse multipath components only. Here, the theory of room electromagnetics is applicable [2], according to which the averaged power delay profile (APDP) decays exponentially. This APDP decay is characterized by the time constant τ_r, referred to as the reverberation time, and the intensity parameter I_{diff} [Hz] [1]. As P_0, the APDP power coefficient of first arriving path, is dependent on the frequency width Δf_0 of the Hann window applied to obtain the APDP, the intensity of the diffuse field will be expressed by the physical parameter I_{diff}, defined by $I_{diff} = P_0 \Delta f_0$ [1]. Based on this theory, an analytical expression of F_{delay} has been developed in [1] in terms of OFDM parameters and the propagation parameters τ_r and I_{diff}.

In this work, a parametric analysis of F_{delay} is carried out as a function of OFDM parameters, based on the aforementioned analytical expression for F_{delay}. This analysis is done for typical IEEE 802.11a/g/n/ac parameters [3] [4]. This gives insight and solutions for the OFDM design to suppress the performance loss due to the propagation delay spread.

II. Determination of F_{delay}

In [1], the performance loss due to the signal distortion over the FFT window (caused by the propagation delay spread), described by a loss factor L_{delay}, has been related to the noise factor F_{delay} as follows:

$$L_{delay} = 1 + \frac{F_{delay}}{F_{lin} IL_{lin}}, \tag{1}$$

where F_{lin} and IL_{lin} are the conventional (linear-scaled) noise factor and implementation loss of the receiver, resp. (i.e., corresponding to the situation where receiver and transmitter are connected by a cable). Therefore, our analysis will be done in terms of F_{delay}.

For the purpose of this work, we rewrite the expression for F_{delay} from [1] as a function of the following relevant OFDM design parameters: the transmit power per frequency unit $P_{T,f}$, the total bandwidth BW of the channel, the FFT period P, CP and the sampling factor f_s. The number of samples per FFT period (N_{sample}) is typically higher or equal than the total number of subcarriers, being $BW \times P$. N_{sample} is usually expressed by means of the sampling factor f_s:

$$N_{sample} = f_s BW P. \tag{2}$$

III. Parametric analysis

In this section, the analytical estimation for F_{delay} is analyzed as a function of P, CP, BW and f_s. All calculations of F_{delay} presented in this work are, unless otherwise mentioned, based on the 802.11a physical standard: $P = 3.2$ µs, $CP = 800$ ns, $BW = 20$ MHz and $f_s = 1$. We assume a typical value for I_{diff} of 6 Hz and a wide range of τ_r varying from 10 ns to 200 ns, based on experimental results [1]. For our calculations, we assume $P_{T,f} = 6.2\ 10^{-9}$W/Hz, based on a 20 dBm transmit power. For a 30 dBm transmit power, F_{delay} can be simply found as 10 dB higher, as F_{delay} is proportional to the transmit power [1].

A. Influence of the cyclic prefix duration CP

In Fig. 1, F_{delay} is shown as a function of CP for different τ_r. F_{delay} decreases strongly with increasing CP, due to the fact that F_{delay} is proportional to $\exp(-CP/\tau_r)$. Although the dependency of F_{delay} on CP is less strong for higher τ_r, increasing CP still provides an efficient strategy to reduce the interference due to delay spread. E.g., for $\tau_r = 140$ ns, F_{delay} decreases from 28.6 dB to 3.8 dB when switching from an 800 ns CP to 1600 ns. This corresponds to a loss L_{delay} reduction of about 14 dB (see (1)). For a 30 dBm transmit power, the decrease of F_{delay} is even from 38.6 dB to 13.8 dB. When switching from an 800 ns CP to 1600 ns, the data rate is reduced with about 17%. However, this is largely compensated by the strong reduction of L_{delay}.

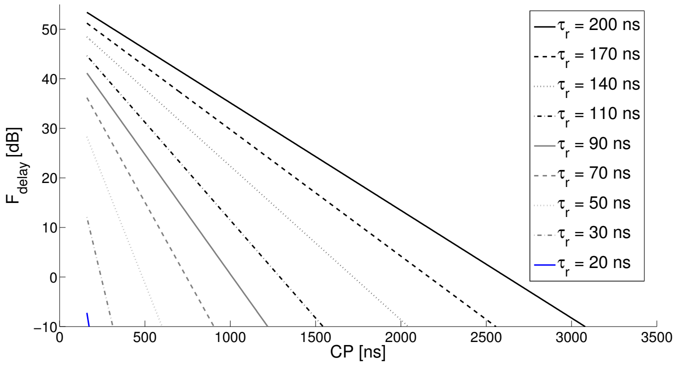

Figure 1. Calculated noise factor F_{delay} as a function of cyclic prefix CP for different reverberation time τ_r. This is based on IEEE 802.11a and a 20 dBm transmit power.

B. Influence of the FFT period P

We found that F_{delay} is inversely proportionally to P. In our analysis, the effect on the theoretical (transmission) data rate R_{data} (proportional to $P/(P + CP)$) and the hardware complexity (related to the number of used subcarriers, proportional to $BW \times P$) is taken into account simultaneously. A higher FFT period P would result in a lower performance loss due to delay spread (F_{delay}) as well as higher data rate, but the FFT processor would also require a higher size. When switching from $P = 3.2$ µs to e.g., 6.4 µs, F_{delay} would decrease with 3 dB and the data rate would increase with 11%. However, the FFT size would increase from 64 to 128. Therefore, increasing P is not really an efficient strategy to suppress the performance loss due to delay spread.

C. Influence of the bandwidth BW

Increasing the bandwidth results into an increased F_{delay} due to a reduced sampling period, which acts as an extension of the cyclic prefix. The dependency of F_{delay} on BW is rather slight. Comparing $BW = 160$ MHz (802.11ac) to 20 MHz, the increase of F_{delay} is only 3 dB for $\tau_r = 50$ ns and 2 dB for $\tau_r = 70$ ns.

D. Influence of the sampling factor f_s

F_{delay} increases slightly for increasing f_s. E.g., when changing f_s from 1 to 4, there is an increase of F_{delay} by 0.6 dB for $\tau_r = 200$ ns and 2.5 dB for $\tau_r = 50$ ns.

IV. Implications to OFDM design

Our analysis shows that, to suppress the noise factor F_{delay} due to delay spread, an efficient strategy is related to the increase of the cyclic prefix length CP (i.e., guard interval (GI)). When switching to a long GI option of 1600 ns (from 800 ns GI), F_{delay} is reduced by even 17.4 dB for $\tau_r = 200$ ns, and by 24.8 dB for $\tau_r = 140$ ns. The data rate R_{data} is reduced by 17%, but this is largely compensated by the strong reduction of F_{delay}.

The strategy of an increased CP is easy with respect to the implementation, but the theoretical data rate R_{data} is reduced. To keep this data rate constant, the ratio between P and CP should be kept constant. As mentioned before, this requires a higher hardware complexity. However, in systems with a higher bandwidth mode, such as 802.11n (40 MHz) and 802.11ac (40/80/160 MHz), the more complex hardware could be combined with the principle of *scaled OFDM* [5]. This would provide a method for systems with a higher bandwidth mode to implement a long GI option for a lower bandwidth mode, without reduction of the (theoretical) data rate and without requiring a complex hardware extension.

V. Conclusion

In this work, the performance loss due to delay spread (in terms of F_{delay}) has been analyzed as a function of OFDM parameters for a wide range of the reverberation time (i.e., $10 - 200$ ns). This loss, caused by diffuse multipath, can be severe: e.g., $F_{delay} = 38.6$ dB for $CP = 800$ ns, a 30 dBm transmit power and a high (but realistic) $\tau_r = 140$ ns. F_{delay} decreases exponentially with increasing CP. E.g., for $\tau_r = 140$ ns, there is a reduction of F_{delay} by about 25 dB, when switching CP from 800 ns to 1600 ns. Further, we found that F_{delay} decreases inversely proportionally with increasing P. Taking into account the implications on the theoretical data rate and the hardware complexity, we propose to adopt a long guard interval option to the 802.11 OFDM standard to ensure reliable reception in high multipath environments. In future research, the analysis presented will be validated experimentally.

References

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